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Measurement of the Charm-Mixing Parameter y_{CP}

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A measurement of the charm-mixing parameter y_{CP} using $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, and $D^0 \to K^-\pi^+$ decays is reported. The D^0 mesons are required to originate from semimuonic decays of B^- and $\overline{B}^0$ mesons. These decays are partially reconstructed in a data set of proton-proton collisions at center-of-mass energies of 7 and 8 TeV collected with the LHCb experiment and corresponding to an integrated luminosity of 3 fb^{-1}. The y_{CP} parameter is measured to be $(0.57 \pm 0.13(\mathrm{stat}) \pm 0.09(\mathrm{syst}))\%$, in agreement with, and as precise as, the current world-average value.

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Neutral charm mesons can change their flavor and turn into antimesons, and vice versa, before they decay. This phenomenon, known as flavor oscillation or D^0–$\overline{D}^0$ mixing, occurs because the eigenstates of the Hamiltonian governing the time evolution of the neutral D system are superpositions of the flavor eigenstates, $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$, where p and q are complex parameters satisfying $|p|^2 + |q|^2 = 1$. In the limit of charge-parity (CP) symmetry, q equals p and the oscillations are characterized by only two dimensionless parameters, $x \equiv (m_1 - m_2)/\Gamma$ and $y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$, where $m_{1(2)}$ and $\Gamma_{1(2)}$ are the mass and decay width of the CP-even (odd) eigenstate $D_{1(2)}$, respectively, and $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$ is the average decay width [1]. The values of x and y are of the order of 1% or smaller [2]. In the presence of CP violation, the mixing rates for mesons produced as D^0 and $\overline{D}^0$ differ, further enriching the phenomenology.

Because of D^0–$\overline{D}^0$ mixing, the *effective* decay width Γ_{CP+} of decays to CP-even final states, such as h^+h^- ($h = K, \pi$), differs from the average width Γ. The latter can be measured in decays that involve an equal mixture of CP-even and CP-odd states, such as $D^0 \to K^-\pi^+$. (Throughout this Letter, the inclusion of the charge-conjugate decay mode is implied unless otherwise stated.) The quantity

$$y_{CP} \equiv \frac{\Gamma_{CP+}}{\Gamma} - 1 \qquad (1)$$

is equal to the mixing parameter y if CP symmetry is conserved. Otherwise, it is related to x, y, $|q/p|$, and $\phi \equiv \arg(q\overline{\mathcal{A}}/p\mathcal{A})$, as $2y_{CP} \approx (|q/p| + |p/q|)y\cos\phi - (|q/p| - |p/q|)x\sin\phi$, where $\mathcal{A}$ ($\overline{\mathcal{A}}$) is the D^0 ($\overline{D}^0$) decay amplitude [3,4]. The approximation holds for decays, such as $D^0 \to h^+h^-$, that can be described by a single amplitude. Neglecting the $\mathcal{O}(10^{-3})$ difference between the phases of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decay amplitudes, ϕ is universal and y_{CP} is independent of the h^+h^- final state.

The current world average value of y_{CP}, $(0.84 \pm 0.16)\%$ [2], is dominated by measurements at the B factories [5,6] and is consistent with the value of y, $(0.62 \pm 0.07)\%$ [2]. The only measurement of y_{CP} at a hadron collider, $[0.55 \pm 0.63(\mathrm{stat}) \pm 0.41(\mathrm{syst})]\%$, has been made by the LHCb Collaboration using a sample of proton-proton collisions corresponding to an integrated luminosity of 29 pb^{-1} [7]. Improving the precision of both y_{CP} and y might lead to evidence of CP violation in D^0–$\overline{D}^0$ mixing if they differ significantly. This would offer sensitivity to a broad class of non-standard-model processes that could contribute to the mixing amplitude by increasing the oscillation rate and/or introducing CP-violation effects that are highly suppressed in the standard model [8–13]. Searches for CP violation in the up-quark sector are also complementary to those performed with beauty and strange mesons, thus providing a unique opportunity to make progress in the understanding of the mechanisms responsible for the observed asymmetry between matter and antimatter in the Universe [14,15].

In this Letter, a measurement of y_{CP} using $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, and $D^0 \to K^-\pi^+$ decays is reported. The D^0 mesons are required to originate from semimuonic decays of B^- or $\overline{B}^0$ mesons, collectively referred to as $\overline{B} \to D^0\mu^-\overline{\nu}_\mu X$. The difference between the widths of D^0 decays to CP-even and CP-mixed final states,

$$\Delta_\Gamma \equiv \Gamma_{CP+} - \Gamma, \qquad (2)$$

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is measured from a fit to the ratio between $D^0 \to K^+K^-$ (or $D^0 \to \pi^+\pi^-$) and $D^0 \to K^-\pi^+$ signal yields as a function of the D^0 decay time. The parameter y_{CP} is then calculated from the measured value of Δ_Γ and the precisely known value of Γ [1] as $y_{CP} = \Delta_\Gamma/\Gamma$. The D^0 decay time is defined as $t = (m\vec{L} \cdot \vec{p})/|\vec{p}|^2$, where m is the known value of the D^0 mass [1], $\vec{L}$ is the vector connecting the $\overline{B}$ and the D^0 decay vertices, and $\vec{p}$ is the momentum of the D^0 meson. The selection efficiency as a function of the D^0 decay time (decay-time acceptance) is very similar for $D^0 \to h^+h^-$ and $D^0 \to K^-\pi^+$ decays. However, since the average opening angle of a two-body decay in the laboratory frame depends on the masses of its decay products, differences of the order of a few percent are present and are corrected for in the analysis. The correction is evaluated using simulation and validated using control samples of data, which also include $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K^+K^-\pi^+$ decays with D^+ decays originating from semimuonic $\overline{B}$ decays (referred to as $\overline{B} \to D^+\mu^-\overline{\nu}_\mu X$). To avoid potential experimenter's bias, the measured value of y_{CP} remained unknown during the development of the analysis and was examined only after the analysis procedure and the evaluation of the systematic uncertainties were finalized.

Semileptonic decays of $\overline{B}$ mesons are partially reconstructed in a data set collected with the LHCb experiment in pp collisions at center-of-mass energies of 7 and 8 TeV and corresponding to an integrated luminosity of 3 fb^{-1}. The LHCb detector is a single-arm forward spectrometer equipped with precise charged-particle vertexing and tracking detectors, hadron-identification detectors, calorimeters, and muon detectors, optimized for the study of bottom- and charm-hadron decays [16,17]. Simulation [18–20] is used to model all relevant sources of decays, correct the data for the decay-time acceptance, study the decay-time resolution, and evaluate systematic uncertainties on the measurement.

The online event selection is performed by a trigger that consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a two-level software stage, which applies a full event reconstruction [21]. To select semimuonic $\overline{B}$ decays, the hardware trigger requires a muon candidate with transverse momentum exceeding 1.5 to 1.8 GeV$/c$, depending on the data-taking period. In the first level of the software trigger, the selected muon is required to be displaced from any pp interaction point. These requirements do not bias the decay time of the D candidate. In the second level of the software trigger, the muon candidate is associated with one, two, or three charged particles, all displaced from the same pp interaction point. This association can bias the decay time, favoring shorter D flight distances, as the muon and the D decay products satisfying the trigger criteria must be consistent with originating from a common displaced vertex.

In the offline reconstruction, the muon candidate is combined with charged particles, forming the D-meson candidate and identified to be either kaons or pions, according to the topology and kinematics of $\overline{B} \to D^0\mu^-\overline{\nu}_\mu X$ and $\overline{B} \to D^+\mu^-\overline{\nu}_\mu X$ decays. The requirements to select $\overline{B} \to D^0\mu^-\overline{\nu}_\mu X$ decays are inherited from the analysis reported in Ref. [22]; those for $\overline{B} \to D^+\mu^-\overline{\nu}_\mu X$ decays are taken from Ref. [23]. In these selections, the D decay products are requested to be displaced from the pp interaction point with respect to which they have the smallest χ^2_{IP}, by imposing $\chi^2_{\text{IP}} > 9$. The χ^2_{IP} is defined as the difference in the vertex-fit χ^2 of a given interaction point reconstructed with and without the particle being considered. These requirements are particularly relevant for the measurement of y_{CP} as they bias the D decay-time distribution, being more efficient for decays with a larger flight distance. The following additional requirements, not used in Refs. [22,23], are applied. The $D\mu$ invariant mass, $m(D\mu)$, must not exceed 5.2 GeV$/c^2$, to suppress genuine charm decays accidentally combined with unrelated muon candidates. The mass of the D candidate must be in the range 1.825–1.920 GeV$/c^2$. Its decay time must be larger than 0.15 ps to minimize a bias observed in simulation at $t \approx 0$ due to the reconstruction of the $\overline{B}$ vertex. A requirement on the component of the D momentum transverse to the $\overline{B}$ flight direction is applied as a function of the corrected $\overline{B}$ mass to suppress decays of b hadrons into final states with a pair of charm hadrons, of which one decays semileptonically, and background from semitauonic decays $\overline{B} \to D\tau^-\overline{\nu}_\tau X$, with $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$. The corrected $\overline{B}$ mass is determined from the $D\mu$ invariant mass as $\sqrt{m^2(D\mu) + p_\perp^2(D\mu)} + p_\perp(D\mu)$, using the momentum of the $D\mu$ system transverse to the $\overline{B}$ flight direction, $p_\perp(D\mu)$, to partially compensate for the momentum of the unreconstructed decay products. After the selection, these background contributions total to at most 1.5% of the signal yield. A contamination of about 1% of D decays produced directly in the pp collision (prompt D) is also estimated to be present in the selected sample. All these background decays are checked to have negligible impact on the measurement of y_{CP}.

Figure 1 shows the D^0 mass distributions of the selected candidates. Prominent signal peaks at the known D^0 mass values are visible on top of a smooth background made of random combinations of charged particles faking a D^0 candidate. The small contamination of prompt D^0 decays is included in the signal peak. Binned χ^2 fits to the mass distributions determine the signal yields reported in Table I, together with the yields of the control samples of D^+ decays. The fits use a probability density function (pdf) consisting of a Johnson S_U distribution [24] (or the sum of a Johnson S_U and a Gaussian distribution in the case of $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays) to

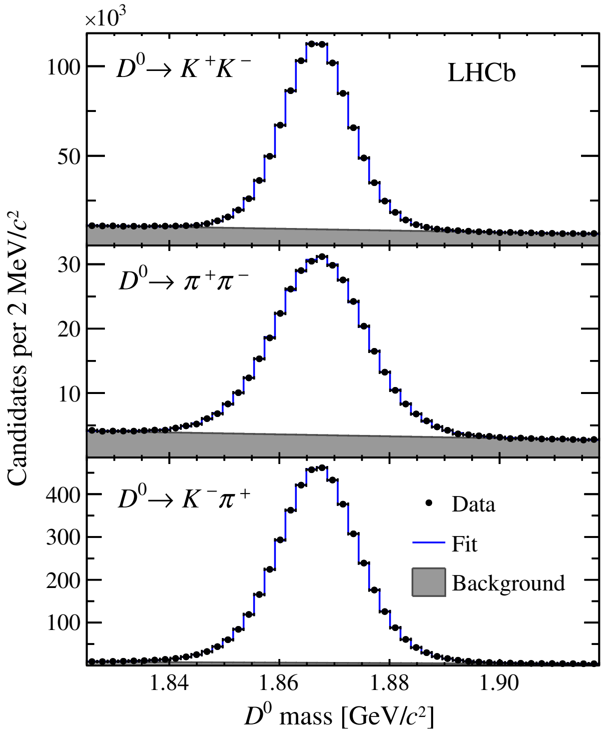

FIG. 1. Distribution of D^0 mass for candidates passing the selection with fit projections overlaid: (top) $D^0 \to K^+K^-$ decays, (center) $D^0 \to \pi^+\pi^-$ decays, and (bottom) $D^0 \to K^-\pi^+$ decays.

describe the asymmetric shape of the signal peak, and a linear distribution to describe the background.

The sample is split into 19 disjoint subsets (bins) of D decay time spanning the range 0.15–4 ps. The signal yields are determined in each decay-time bin with fits to the D mass distribution using the same pdf as described above. In these fits all signal-shape parameters are fixed to the values from the decay-time-integrated fits, with the exception of the mean and width of the Johnson function. The ratio between $D^0 \to K^+K^-$ (or $D^0 \to \pi^+\pi^-$) and $D^0 \to K^-\pi^+$ signal yields as a function of decay time is fitted to determine the value of Δ_Γ. The fit minimizes a χ^2 function where the signal-yield ratio in a decay-time bin is described by the ratio of the integrals of two decreasing exponential functions, one for the numerator with exponent $\Gamma_{CP+} = \Delta_\Gamma + \Gamma$, and the other for the denominator with exponent Γ. The value of Γ is fixed to its world average of 2.4384 ps^{-1} [1], while Δ_Γ and a decay-time-independent normalization factor of the ratio are free to vary in the fit. It should be noted that Γ can be fixed to any arbitrary value, since the distribution of the ratio is only sensitive to Δ_Γ. In the fit, the signal-yield ratio is corrected in each decay-time bin by a factor calculated as the ratio of the decay-time acceptances of the decays in the numerator and the denominator. This correction is determined from simulation and shows up to 6% variations around unity as a function of D^0 decay time (Fig. 2). The correction is similar in magnitude, but with an opposite trend as a function of t, for the determination of Δ_Γ with $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays.

TABLE I. Signal yields of the selected candidates.

Decay	Signal yield [10^3]
$D^0 \to K^+K^-$	878.2 ± 1.2
$D^0 \to \pi^+\pi^-$	311.6 ± 0.9
$D^0 \to K^-\pi^+$	4579.5 ± 3.2
$D^+ \to K^-\pi^+\pi^+$	2260.2 ± 1.9
$D^+ \to K^+K^-\pi^+$	98.0 ± 0.3

Several null tests are performed on data to prove that the estimates of the signal yields are unbiased, and that the corrections from simulation are reliable. The tests use samples of (i) $D^+ \to K^+K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays, (ii) $D^+ \to K^-\pi^+\pi^+$ decays, (iii) $D^0 \to K^-\pi^+$ decays, and (iv) $D^0 \to K^+K^-$ decays. In test (i), the width difference is measured by fitting the yield ratio of $D^+ \to K^+K^-\pi^+$ to $D^+ \to K^-\pi^+\pi^+$ decays. The corrections for the ratio of decay-time acceptances are similar to those in the y_{CP} measurement. In tests (ii)–(iv), the selected data are split randomly into two independent sets: one is used as the denominator sample, and the other, featuring a tighter requirement of $\chi^2_{\rm IP} > 60$ for the D decay products, is used as the numerator sample. The threshold on $\chi^2_{\rm IP}$ is chosen such that the ratio of decay-time acceptances deviates from a constant by up to 40%, i.e., almost an order of magnitude larger variation than that present in the y_{CP} measurement. In all tests, the measured decay-width difference is consistent with zero, with fit p values ranging from 8% to 84%. The two most precise tests, (ii) and (iii), correspond to a validation of the measurement of y_{CP} with an uncertainty of 0.14%, which includes the limited knowledge of the decay-time acceptance correction. Another test (v) consists in measuring the decay-width difference of D^+ and D^0 mesons, using the largest-yield samples of $D^+ \to K^-\pi^+\pi^+$

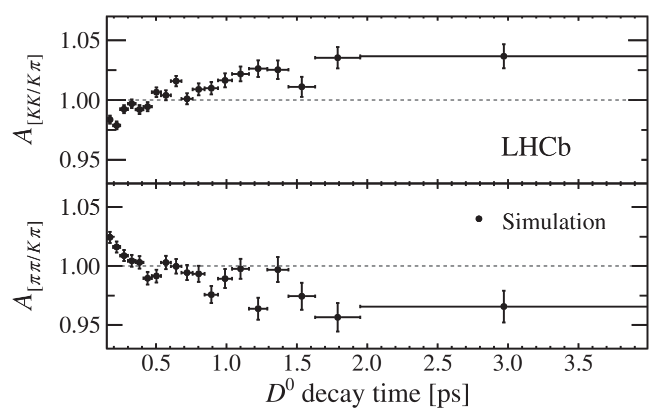

FIG. 2. Ratio of decay-time acceptances from simulation for (top) $D^0 \to K^+K^-$ over $D^0 \to K^-\pi^+$ decays and (bottom) $D^0 \to \pi^+\pi^-$ over $D^0 \to K^-\pi^+$ decays.

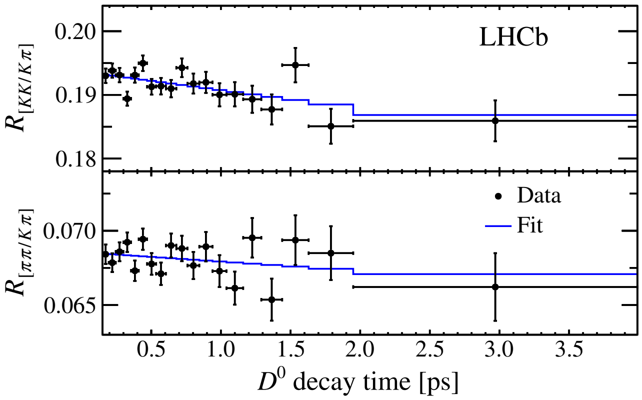

FIG. 3. Acceptance-corrected signal-yield ratio of (top) $D^0 \to K^+K^-$ over $D^0 \to K^-\pi^+$ decays and (bottom) $D^0 \to \pi^+\pi^-$ over $D^0 \to K^-\pi^+$ decays as a function of D^0 decay time, with fit projection overlaid.

and $D^0 \to K^-\pi^+$ decays. In this measurement, the ratio of the decay-time acceptances presents variations up to about 10%. However, the decays considered in the numerator and the denominator have sufficiently different topologies that potential biases on the measurement of the width difference are not suppressed in the ratio at the same level as in the y_{CP} measurement. In addition, the very different lifetimes between D^+ and D^0 mesons lead to a signal-yield ratio spanning over a very broad interval, with a maximum approximately 25 times larger than its minimum. The ratio of D^+ to D^0 lifetimes is determined to be 2.5141 ± 0.0082, where the uncertainty is only statistical, in agreement with the known value of 2.536 ± 0.019 [1]. Biases that scale with Δ_Γ are excluded by this test within a relative precision of about 1%. In summary, the five tests yield results consistent with the expectations with a χ^2 of 5.5, which corresponds to a p value of 36%. The tests demonstrate that the acceptance effects needed for the measurement of y_{CP} are understood within the precision provided by the limited size of the simulated samples. The tests also confirm that background originating from prompt D decays, from b-hadron decays to double-charm final states, and from semitauonic $\overline{B}$ decays can be neglected. They contaminate all samples considered in the tests with fractions similar to those estimated in the y_{CP} measurement.

Figure 3 shows the acceptance-corrected signal-yield ratio measured for the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays with respect to $D^0 \to K^-\pi^+$ decays, with fit projections overlaid. The obtained values of Δ_Γ and y_{CP} are reported in Table II. The use of a common reference sample ($D^0 \to K^-\pi^+$) does not introduce any significant correlation between the statistical uncertainties of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ measurements.

Systematic uncertainties of 0.0027 ps^{-1} (0.0038 ps^{-1}) on Δ_Γ, and therefore 0.11% (0.15%) on y_{CP}, are assigned for the measurement done with $D^0 \to K^+K^-$ ($D^0 \to \pi^+\pi^-$) decays. The correlation between the systematic uncertainties is 5%. They are dominated by the knowledge of the correction for the ratio of decay-time acceptances, which is limited by the finite size of the simulated samples. This yields systematic uncertainties of 0.0026 ps^{-1} (0.0037 ps^{-1}) on Δ_Γ and 0.11% (0.15%) on y_{CP}, which are uncorrelated between the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ measurements. Other systematic uncertainties, contributing less, are associated with the assumed decay model and composition of the simulated samples of semileptonic $\overline{B}$ decays (0.0006 ps^{-1} on Δ_Γ, 0.02% on y_{CP}), possible biases introduced by the fit method as determined in large ensembles of pseudoexperiments (0.0004 ps^{-1} on Δ_Γ, 0.02% on y_{CP}), and the neglected 0.12 ps decay-time resolution (0.0003 ps^{-1} on Δ_Γ, 0.01% on y_{CP}). These systematic uncertainties are fully correlated between the measurements with $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays. Asymmetric production of D^0 and $\overline{D}^0$ mesons from semileptonic B^- and $\overline{B}^0$ decays produce biases on y_{CP} that are smaller than 10^{-5}. Uncertainties on the measured decay-length arising from relative misalignments of subdetectors and the uncertainty of the input value of Γ, 2.4384 ± 0.0089 ps^{-1} [1], which is used to determine y_{CP} from Δ_Γ, have negligible contributions. Finally, consistency checks based on repeating the y_{CP} measurement on independent subsamples chosen according to data-taking periods, trigger-selection criteria and interaction-point multiplicity all yield compatible results within statistical fluctuations.

TABLE II. Measured values of Δ_Γ and y_{CP}. The first uncertainty is statistical, the second is systematic.

Decay	Δ_Γ [ps^{-1}]	y_{CP} [%]
$D^0 \to K^+K^-$	$0.0153 \pm 0.0036 \pm 0.0027$	$0.63 \pm 0.15 \pm 0.11$
$D^0 \to \pi^+\pi^-$	$0.0093 \pm 0.0067 \pm 0.0038$	$0.38 \pm 0.28 \pm 0.15$

In summary, the charm mixing-parameter y_{CP} is measured using $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, and $D^0 \to K^-\pi^+$ decays originating from semileptonic B^- and $\overline{B}^0$ decays produced in pp collision data collected with the LHCb experiment at center-of-mass energies of 7 and 8 TeV, and corresponding to an integrated luminosity of 3 fb^{-1}. The results from $D^0 \to K^+K^-$, $y_{CP} = [0.63 \pm 0.15(\mathrm{stat}) \pm 0.11(\mathrm{syst})]\%$, and $D^0 \to \pi^+\pi^-$ decays, $y_{CP} = [0.38 \pm 0.28(\mathrm{stat}) \pm 0.15(\mathrm{syst})]\%$, are consistent with each other and with determinations from other experiments [2]. The value of y_{CP} measured in the $D^0 \to K^+K^-$ mode is the most precise to date from a single experiment. The two measurements are combined and yield $y_{CP} = [0.57 \pm 0.13(\mathrm{stat}) \pm 0.09(\mathrm{syst})]\%$, which is consistent with and as precise as the current world average value, $(0.84 \pm 0.16)\%$ [2]. The result is also consistent with the known value of the mixing parameter y, $(0.62 \pm 0.07)\%$ [2], showing no evidence for CP violation in D^0–$\overline{D}^0$ mixing.

As larger data samples are accumulated by LHCb, the dominant systematic uncertainty due to finite simulation samples will also be reduced, giving good prospects for further reduction in the uncertainty of y_{CP}.

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